Marine Policy 116 (2020) 103712

Contents lists available at ScienceDirect

Marine Policy

journal homepage: http://www.elsevier.com/locate/marpol

Cold-water corals and deep-sea sponges by-catch mitigation: Dealing with groundfish survey data in the management of the northwest Atlantic Ocean high seas fisheries

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ARTICLE INFO

Keywords:
By-catch mitigation
High seas fisheries
Northwest Atlantic Ocean
Spatial management
VME

ABSTRACT

The integration of survey data in the processes of the Regional Fisheries Management Organisations is a key step for conservation of deep-sea ecosystems and sustainable exploitation of deep-sea fisheries resources, including the mitigation of by-catch and discards of cold-water corals and deep-sea sponges, both considered by FAO as vulnerable marine ecosystems (VMEs) indicator species. Information on corals and sponges from annual bottom trawl groundfish surveys in areas beyond national jurisdictions has been integrated into the "ecosystem management cycle" of the Northwest Atlantic Fisheries Organization (NAFO). Survey data have improved our knowledge on VMEs identification, distribution and extent, and has led to the proposal and implementation of conservation and management measures. These data have particular relevance to delineate and refine the boundaries of areas closed to commercial bottom fishing (14 closures), in order to prevent significant adverse impacts on VMEs, according to the mandate of United Nations General Assembly Resolution 61/105. Considering the European groundfish surveys in the NAFO Regulatory Area (high seas) as a case study, the paper presents an overview of how invertebrate catch data have been integrated into the fisheries management process as a basis to the implementation of VMEs closed areas. Fishing closures are considered effective spatial management measures to avoid by-catch and discards of cold-water corals and deep-sea sponges in commercial bottom fishing, mitigating the adverse impacts on deep-sea ecosystems.

1. Introduction

1.1. By-catch of cold-water corals and deep-sea sponges in high seas fisheries

Deep-sea bottom fisheries, just like some other human activities carried out in the high seas (e.g. hydrocarbon exploration and exploitation, seafloor mining, etc.) may produce disturbance and potential significant adverse impacts (SAI) on cold-water corals and deep-sea sponges, being a matter of concern [1] for the regional fisheries management organisations (RFMOs). Corals and sponges, as erect and fragile invertebrates, are especially vulnerable to bottom fishing-induced impacts. Particularly, bottom fishing gears can catch unwanted and non-targeted cold-water corals and deep-sea sponges when their spatial distributions overlap with the fishing footprint [2,3].

Since 2006, several United Nations General Assembly (UNGA) Resolutions on sustainable fisheries [4–6] have called states to adopt urgent measures, either through RFMOs or by themselves, in order to protect VMEs in areas beyond national jurisdictions (ABJN), with special reference to preserve cold-water corals and deep-sea sponges. According to the United Nations Food and Agriculture Organisation (FAO) International Guidelines for Management of Deep-sea Fisheries on the High Seas [7], the most vulnerable ecosystems are those that can be easily disturbed and which either recover very slowly or never recover at all. Both cold-water corals and deep-sea sponges were considered by the FAO as examples of VMEs indicator species. Moreover, the Guidelines provide tools and guidance to the sustainable use of marine living resources and the prevention of SAI on VMEs. SAI were defined as those that compromise ecosystem structure or function, in a manner that: (i) impairs the ability of affected populations to replace themselves, (ii) degrades the long-term natural productivity of habitats, and (iii) causes, on more than a temporary basis, significant loss of species richness,

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https://doi.org/10.1016/j.marpol.2019.103712
Received 25 October 2018; Received in revised form 4 July 2019; Accepted 4 October 2019
Available online 17 October 2019

habitat or community types. When determining SAI, six factors should be considered: (i) intensity or severity of the impact, (ii) spatial extent of the impact, (iii) sensitivity/vulnerability of the ecosystem, (iv) ability of an ecosystem to recover, (v) extent to which ecosystem functions may be altered and (vi) timing and duration of the impact. Therefore there arises a need for implementing management approaches to avoid by-catch of cold-water corals and deep-sea sponges in the high seas fisheries, in order to prevent SAI. The Northwest Atlantic Fisheries Organization (NAFO) is the RFMO with competence on fisheries management and VMEs conservation in international waters of the Northwest Atlantic Ocean (www.nafo.int). Since 2007, NAFO has been adopting spatial management measures to protect cold-water corals and deep-sea sponges in the Regulatory Area [8]. Data from the groundfish surveys presented in this paper, together with other information (e.g. ecosystem data and fishing effort), have been used by NAFO, as baseline information to underpin most of such measures.

1.2. Objectives of this paper

This paper presents a case study of how invertebrate catch data from groundfish surveys in the NAFO Regulatory Area, particularly the surveys funded by the European Union (EU) [9,10], together with other sources (e.g. the NEREIDA[1] programme [11]), have been integrated in the NAFO process as a basis to underpin spatial management measures in ABJN. Survey methodology is presented as well as the methods used to identify sea pen fields, gorgonian coral VMEs and sponge grounds, and to assess SAIs. Management results are summarised with focus on mitigation of by-catch of cold-water corals and deep-sea sponges in commercial fisheries, based on the delineation of areas closed to bottom fishing. This is followed by a discussion on the role that fish stock assessment bottom trawl surveys have played in identifying VMEs, the challenges of this approach and the monitoring alternatives. Finally, the conclusions from the experience of the EU surveys are briefly outlined.

2. Role of groundfish surveys in identifying VMEs in the high seas

2.1. Case study - EU groundfish surveys in the northwest Atlantic Ocean

To investigate the role of groundfish surveys in the process of identification of VMEs in ABJN, the EU annual groundfish surveys in the northwest Atlantic Ocean was described, and then the links to the NAFO advice were analysed. Case study is located in international waters, to the east of the Canadian coastline, at depths from 40 m to 1,450 m approximately. This area corresponds to a part of the Grand Banks of Newfoundland and its slopes, the top and the slopes of Flemish Cap, and the deep bottoms of the Flemish Pass that separate the two above mentioned features. The study area (Fig. 1) covers the main international bottom fishing grounds, known as the NAFO footprint (existing bottom fishing areas) [12], for Greenland halibut, cod, skate and redfish, located on the high seas within the NAFO Regulatory Area (NAFO Divisions 3LMNO). It is worthy of note that the EU surveys are the only survey series in the NAFO Regulatory Area that covers the whole NAFO footprint [13] in trawlable grounds (Fig. 1). Other existing surveys (Table 1) do not adequately cover the Flemish Cap (NAFO Division 3 M), the main high seas fishing ground for cod and an important fishing area for Greenland halibut and redfish. Flemish Cap hosts sea pen fields and sponge grounds and most of the fishing closures to protect VMEs. These were the reasons why in this article the EU surveys were chosen as a case study, as they are crucial for advice on both VMEs and fisheries in the NAFO context.

There are two EU annual groundfish surveys in the NAFO Regulatory Area: (i) The EU-Spain 3LNO groundfish survey in the Grand Banks of Newfoundland (NAFO Divisions 3NO) and the Flemish Pass (NAFO Division 3L), between 40 and 1,450 m depth, and (ii) the EU-Spain & Portugal 3M groundfish survey in the Flemish Cap (NAFO Division 3M) at depths ranging between 130 and 1,450 m. EU surveys started in 1988 in Division 3M and later were expanded to Divisions 3LNO. Since 2003, they were carried out with the Spanish research vessel "Vizconde de Eza". The main objective of these surveys was the assessment of fish stocks. They have been co-funded by the EU through the European Maritime and Fisheries Fund within the National Program of collection, management and use of data in the fisheries sector and support for scientific advice regarding the Common Fisheries Policy. Both surveys are included in the EU list of mandatory research surveys at sea for informing stock assessment and fisheries management [14].

Surveys were conducted between late spring and summer, using a random-stratified sampling design [15], with standardized 30-min bottom trawls and towing speed of ~3 knots. The study of VME indicator species was the responsibility of the Spanish Institute of Oceanography (IEO). This work was initiated in 2005 under the ECOVUL/ARPA project and the related predoctoral research grant [16], as a reply to the UNGA requirements [4,11], laying the foundations for VME monitoring. Catch of invertebrates was studied haul by haul. At each haul, trawl gear characteristics, location, date, time and depth at start and end of trawl were recorded. All the invertebrates captured were sorted and identified at the lowest possible taxonomic level. Catches were recorded and weighed on board (live weight), particularly cold-water corals and deep-sea sponges [9,10]. The number of individuals or colonies was noted when possible. Samples were taken as voucher specimens for subsequent final identification in the laboratory.

2.2. Uses of coral and sponge groundfish catch data: the NAFO approach

One of the first questions to be resolved when studying VMEs is to know which particular vulnerable species and taxa occur in the fishing grounds (see Section 2.2.1). The next relevant point is to get a picture of their geographic and bathymetric distribution (see Section 2.2.2), and then provide advice on protection measures, such as spatial management measures to prevent by-catch and other impacts (see Section 2.2.3). Finally, according to the FAO Deep-sea Fisheries Guidelines [7], SAI of bottom fishing must be assessed (see Section 2.2.4). Analyses of catch data collected in groundfish surveys allowed NAFO to progress in addressing these challenges. The catch-based approach [17] guided the study of VMEs according to the criteria provided by FAO [7], consistent with the identification of structure-forming habitats [8]. Table 2 shows a summary of the type of analyses performed, the advice derived from it and the management measures adopted.

The dataset from EU groundfish surveys contain 14-years (2005–2018) of information on benthic invertebrates, covering the whole NAFO footprint (trawlable grounds). The EU dataset was integrated within a GIS. Data and distribution maps of significant concentrations of cold-water corals and deep-sea sponges were annually updated by IEO scientists and were presented to the NAFO Working Group on Ecosystem Science and Assessment (WGESA), formerly named Working Group on Ecosystem Approach to Fisheries Management (WGEAFM) [18] for VMEs identification and mapping. WGESA meets annually and provides guidance to NAFO Scientific Council on specific ecosystem-related issues and requests [19]. The flowchart of Fig. 2 shows how the VME data from groundfish surveys and other sources considered by NAFO (Table 1) are annually integrated into the NAFO "ecosystem management cycle", contributing to put into practice the "NAFO Roadmap", a general framework aimed towards implementing an Ecosystem Approach to Fisheries in NAFO [20].

2.2.1. VMEs identification

As a result of the analysis of invertebrate associations in the catch of groundfish surveys, two main groups of cold-water corals were

[1] International multidisciplinary research programme for the study and protection of VMEs within the NAFO Regulatory Area.

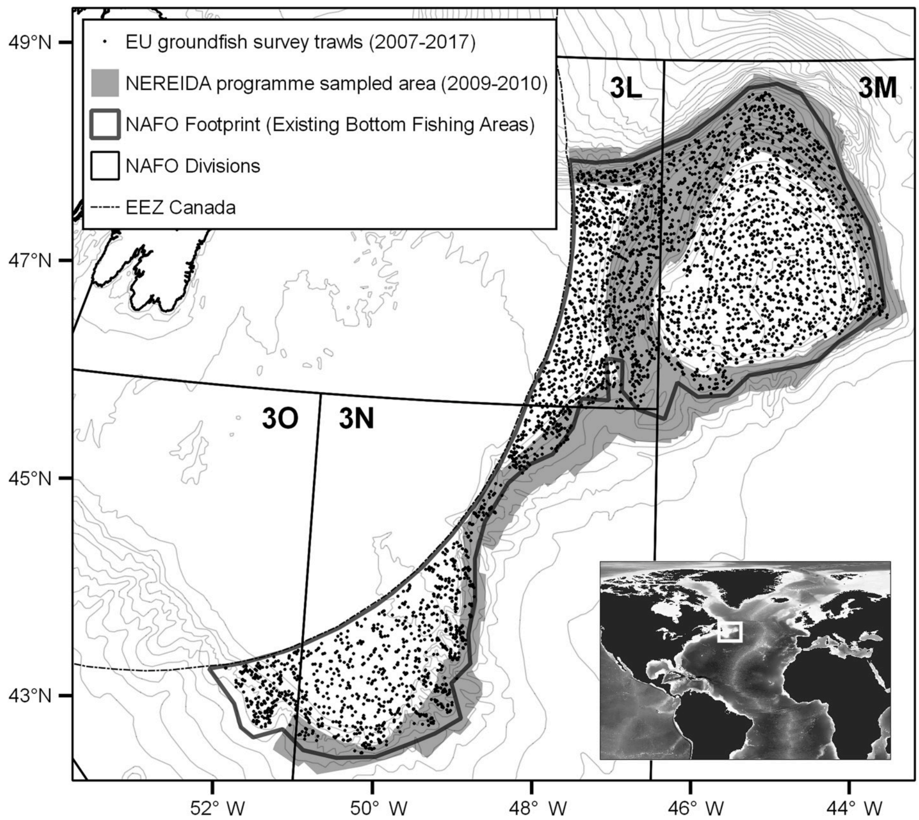

Fig. 1. Map of the study area in international waters of the northwest Atlantic Ocean, showing the location of the trawls from the EU Groundfish surveys (2007–2017) and the sampled area from the NEREIDA multidisciplinary programme (2009–2010). The study area covers the existing bottom fishing areas in the NAFO Regulatory Area (NAFO footprint [12]).

Table 1
Main data sources considered by NAFO for the advice on VME within the fishing footprint.

Country	Data source	Data collected
EU-Spain	GS	Invertebrate catch
EU-Spain & Portugal	GS	Invertebrate catch
Canada	GS	Invertebrate catch
EU-Spain	N	Multibeam bathymetry
EU-Spain	N	Seismic profiles
EU-Spain	N	CTD
EU-Spain	N	Rock dredges
EU-Spain	N	Box corers
Canada	N	Push corers
Canada	N	Video footage
Canada	N	Photos
NAFO contracting parties	VMS	Effort data

GS: Groundfish surveys (bottom trawls), N: NEREIDA multidisciplinary surveys; VMS: Vessel Monitoring System.

identified by NAFO as indicators of VMEs [17,19], following the FAO [7] criteria, considering biomass: (i) gorgonians (Order Alcyonacea) and (ii) sea pens (Order Pennatulacea). Colonial stony corals (Order Scleractinia) are known vulnerable species (e.g. *Lophelia pertusa*) in seamounts, canyons and steep topographies [21,22] but they are rare inside the bottom fishing footprint [12,17]. Conversely, black corals (Order Antipatharia) were not considered, since the results from NEREIDA rock dredge samples indicate that they are sparsely but widely distributed [8]. Sponges (Phylum Porifera) were also considered as VMEs indicators, particularly Suborder Astrophorina which comprises massive, spherical or cheese-shape species. The weight of sponge catch can be used as an indicator of the sponge dominated communities (sponge grounds) [23]. Besides the above mentioned taxa, the full list of VME indicator species [12,19] identified by NAFO based on a review of all invertebrate species taken in research vessel surveys, included also tube-dwelling anemones (Ceriantharians), erect bryozoans, sea lilies (Crinoids) and sea squirts (Tunicates).

2.2.2. *VMEs distribution and extent*

Under the structure-forming criterion, a VME is a regional habitat that contains VME indicator species at or above significant concentration levels [18]. NAFO developed a quantitative methodology approach for the determination of significant concentrations of cold-water corals and deep-sea sponges from groundfish survey catch data. The aim of this approach was to identify catch weight thresholds associated with the formation of highly aggregated groups of such vulnerable species, which could be considered to be indicative of a VME. Catch-based information was used later to (i) map the location of significant concentrations of cold-water corals and deep-sea sponges considered VMEs and (ii) underpin the implementation of spatial management measures. From the practical point of view, mapping the location of significant concentrations from groundfish survey data, has been the basis for the delineation of the areas closed to bottom fishing activities to protect cold-water corals and deep-sea sponges within the fishing footprint [17,18,23]. This seems that at present, EU groundfish surveys thanks to their wide temporal, spatial and bathymetrical sampling coverage, are essential for advice on VMEs.

Since 2009 the kernel density estimation [13] is being used by NAFO as a primary quantitative method to determine the distribution and extent of cold-water corals and deep-sea sponges vulnerable ecosystems. This method identifies "hotspots" in the biomass distribution derived from the groundfish survey catch data, by looking at natural breaks in the spatial distribution related to changes in local density. These natural breaks allow defining of significant VMEs polygons (kernel density-derived VMEs polygons) [1]. The kernel density estimation

Table 2
EU groundfish surveys in the NAFO Regulatory Area: Summary of the advice derived from the survey data and the related management measures adopted by NAFO within the fishing footprint.

Advice				Management		
Year	Methods	Contribution to the advice	References	Year	Related measures	References
2005	Start of the VME data collection.	Benthic invertebrate database (geo-referenced catch data) and samples from groundfish surveys within the fishing footprint.	Murillo et al. (2008) [69].	–	–	–
2008	Mapping of VME indicator species and GIS.	Identification of VME priority areas and VME candidate areas.	Murillo et al. (2008) [69]; WGEAFM (2008) [70].	–	–	–
2008	Cumulative catch distributions and GIS.	Identification of coral taxa and coral associations. Selection of catch weight thresholds for the identification of significant concentrations of corals. Identification of coral key locations.	WGEAFM (2008) [17]; Murillo et al. (2011) [9].	2008	3O Coral Area Closure: 1 closure enforced.	NAFO CEM (2008) [71].
2009	Kernel density analyses and GIS.	Identification of sponge taxa which have interactions with commercial fisheries. Selection of catch weight thresholds for the identification of significant concentrations of sponges. Location of sponge grounds.	WGEAFM (2009) [23]; Murillo et al. (2012) [10].	2010	High Sponge and Coral Concentration Area Closures: 11 closures enforced.	NAFO CEM (2010) [72].
2011	Mapping of VME indicator species.	List of VME indicator species.	WGEAFM (2011) [19].	2013	List of VME indicator species.	NAFO CEM (2013) [73].
2013	Kernel density analyses and GIS	Update of catch weight thresholds for the identification of significant VME concentrations.	WGESA (2013) [18]; Kenchington et al., 2014 [13].	–	–	–
2013	Mapping of VME indicator species and GIS.	Location of significant research vessel trawl catches of VME corals and sponges. Update of the NAFO Guide of the Identification of Vulnerable Marine Ecosystem (VME) indicator taxa.	WGFMS (2013) [75]; Scientific Council Meeting (2012) [74]; WGESA (2014) [30].	2014	Areas 2, 7, 8, 10 were modified. A new closure was added (Area 12): 12 closures enforced. VME indicator species identification guide available to be used in exploratory fisheries.	NAFO CEM (2014) [76]; Kenchington et al., 2015 [25].
2014	Kernel density analyses and SDM	Maps of probability of different VME indicator species occurrence. Review of closed areas in the NRA.	WGESA (2013) [18]; WGEAFFM (2014) [77]; General Council and its Subsidiary Body (STACFAD) (2014) [78].	2015	Area 4 was modified. A new closure was added (Area 13): 13 closures enforced.	NAFO CEM (2015) [79].
2016	Kernel density analyses and SDM; NAFO analytical approach for assessing SAI	Assessment of SAI on VMEs by bottom fishing activities	Scientific Council Meeting (2016) [1].	–	–	–
2016	Mapping of VME indicator species and GIS.	Location of significant research vessel trawl catches of coral and sponge VME	WGEAFFM (2016) [56]; Scientific Council Meeting Report (2016) [31].	2017	A new closure was added (Area 14): 14 closures enforced.	NAFO CEM (2017) [80].
2018	Mapping of VME indicator species and GIS.	Location of significant research vessel trawl catches of coral and sponge VME. Update of list of VME indicator species.	WGEAFFM (2018) [81]; NAFO Commission and its Subsidiary Bodies (STACTIC and STACFAD) (2018) [82]; WGESA (2018) [67]; Murillo et al., 2016 [83].	2019	Area 14 was reopened: 13 closures enforced.	NAFO CEM (2019) [12].

method incorporates the spatial dimension to assist in defining weight threshold values of research vessel catches for delineating VMEs. This method does not explicitly take into account the habitat characteristics. Therefore, a combination of species distribution models for sponges, black corals, sea pens and gorgonians [18,24], together with the outputs from a predictive model focused on biomass data from groundfish surveys and NEREIDA benthic variables, was used to re-define the extent of VME kernel density polygons [1]. As a part of the methodology, the selection of appropriate catch weight thresholds for the evaluation of the groundfish surveys hauls was a key step to assist the identification of significant concentrations of VME indicator species or taxa, in order to map the polygons delineating the distribution and extent of VME [18, 23]. Cold-water corals and deep-sea sponge catch weight thresholds considered to be indicative of a significant concentration, have been defined for surveys [13]: (i) 0.15 kg per haul for small gorgonians (e.g. Family Isididae), (ii) 0.6 kg per haul for large gorgonians (e.g. Family Paragorgiidae), (iii) 1.4 kg per haul for sea pens and (iv) 75 kg per haul for Large-sized sponges (e.g. Suborder Astrophorina). The references about size ranges were provided in the NAFO VME identification guide [25]. The map of Fig. 3 shows the combined extent of the re-defined sea pen fields, gorgonian corals and sponge grounds. According to NAFO [1] these indicator taxa are unlikely to occur in significant concentrations outside of the extent of the re-defined VME polygons.

2.2.3. VMEs protection through spatial management measures

NAFO considered that management through the closing to bottom fishing of areas with significant concentrations of VME indicator species is the most effective measure for the protection of VMEs [8]. So, in year 2007, in line with the mandate of UNGA Resolution 61/105, first closures were implemented to protect several seamount complexes. Later in 2008, a coral protection zone was adopted in NAFO Division 3O. Since 2010, several closures to protect sponge and coral concentrations have been adopted in NAFO Divisions 3LMN. At the present date, there are a

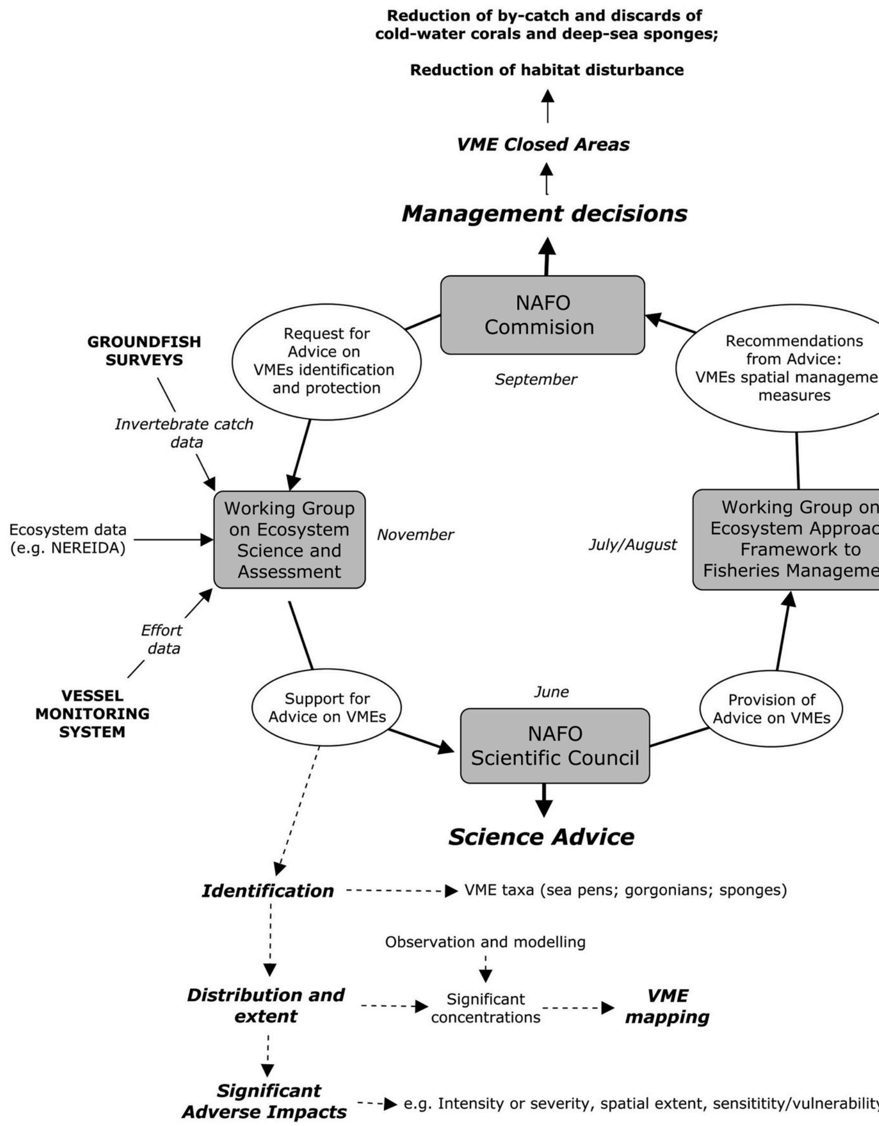

Fig. 2. Flowchart showing the integration of the data into the NAFO "Ecosystem Management Cycle" in the context of the VMEs advice process. Adapted from Koen-Alonso et al. [20].

total of 20 fishing closures[2] within the Regulatory Area. Of these closures, 6 correspond to seamounts and 14 are totally, or partly, inside the fishing footprint (Fig. 3). In this case, catch data collected from groundfish surveys are being annually updated for assessment of significant concentrations of cold-water corals and deep-sea sponges, underpinning the advice on area closures.[3] Of the above mentioned 14 closures adopted [12], a total of 11 closed areas were located within the Flemish Cap (Division 3 M), which indicates the relevance of the EU groundfish survey data.

2.2.4. *Significant adverse impacts*

NAFO [1] developed an approach for the assessment of SAI on VMEs. Between the six factors considered by FAO [7] to determining SAI (see Section 1.1), the first three are being addressed by NAFO and the last three will be addressed in the near future [26]. *Intensity or severity of the impact* of fishing on the VME was evaluated based on the VMEs indicators identified from groundfish research vessel surveys (see Section 2.2.1), through a literature review [27,28] supplemented by the outcomes from SAI assessment. According to the literature review and the biomass cut-off values identified in the SAI analysis [1], sponges and gorgonian corals were considered extremely vulnerable. Sea pens were also vulnerable but they appeared to be more resilient and this issue is currently being studied [29]. To assess the *spatial extent of the impact*, the location of sea pen fields, gorgonian corals and sponge grounds were mapped based on groundfish survey data, and then the percentages of the area impacted by fishing, the area protected by closed areas and the area at risk of impact were calculated using the analytical approach described by NAFO [1]. This approach uses (i) VMEs biomass observations from groundfish survey catch data (cumulative distribution of biomass) in conjunction with (ii) fishing effort data from VMS, to determine cut-offs in VMEs species biomass, (iii) the re-defined kernel density-derived VMEs polygons to identify the biogeographical limits of VMEs and (iv) the location of current VMEs closed areas (they are protected and can be excluded from the assessment). Once the predicted extent of VMEs is determined, the area at risk of SAI can be defined through an integrated analysis of fishing intensity and the spatial

[2] See "FAO VME Portal and Database" (http://www.fao.org/in-action/vulnerable-marine-ecosystems/en) for information on NAFO closures (interactive maps and factsheets).

[3] The next global review of the area closures will be undertaken by NAFO in year 2020 [8].

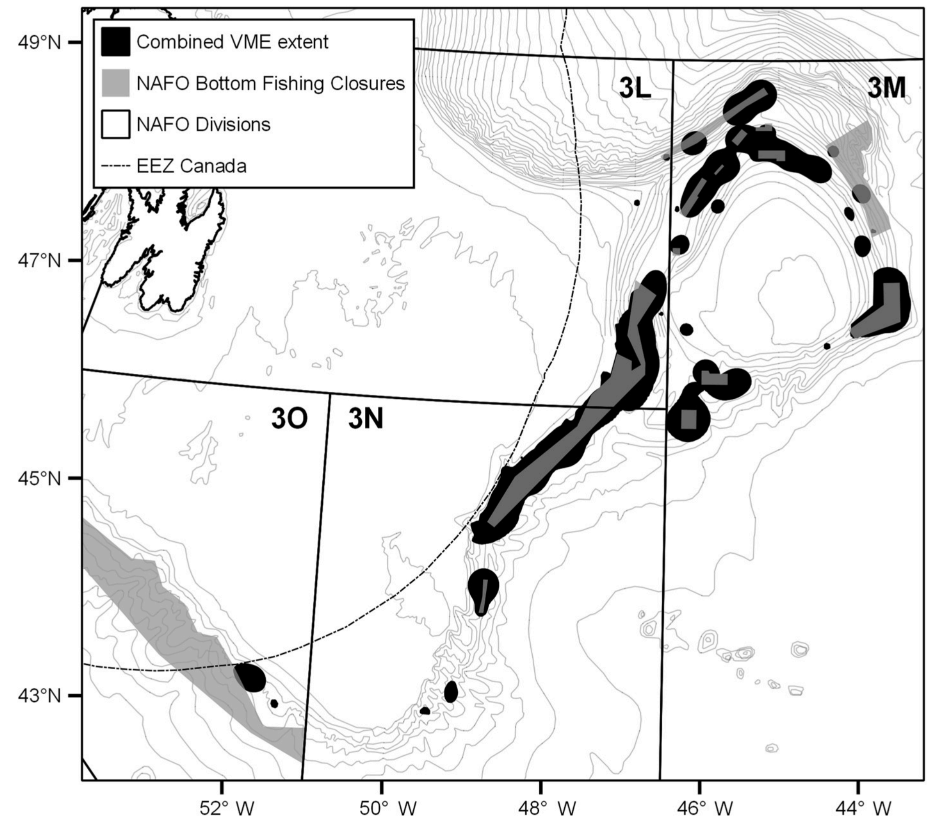

Fig. 3. Map of study area showing the combined extent of VMEs (sponges, sea pens and gorgonians) in the NAFO Regulatory Area [1], as well as the bottom fishing closures implemented by NAFO within the fishing footprint (NAFO Conservation and Enforcement Measures for 2019 [12]).

distribution of VMEs biomass [30]. The evaluation of the *spatial extent*, including an *index of VME sensitivity* was performed by NAFO in 2016 [31]. Several SAI criteria were quantitatively evaluated, meanwhile, the overall risk of SAI was evaluated as "qualitative category" using expert judgment achieved by consensus (Table 3). The qualitative risk scores were determined by expert evaluation of the quantitative data.

Table 3
Quantitative and overall assessment of SAI conducted by NAFO for sponge, sea pen and large gorgonian VME. Source: NAFO [1,31].

SAI criteria	Sponge		Sea pen		Large gorgonian	
	Area	Biomass	Area	Biomass	Area	Biomass
Low risk[a,h]	65%	73%	16%	19%	56%	63%
High risk[b,h]	14%	10%	46%	39%	12%	14%
Impacted[c,h]	21%	17%	38%	42%	31%	23%
VMEs overlapping[d,h]	11%		2%		74%	
Index of sensitivity[e,h]	0.3		0.5		0.1	
Fragmentation[f,h]	1%		26%		2%	
Fishing area stability[g,h]	32%		14%		21%	
Overall risk of SAI[i]	Low		High		Low	

[a] It falls within a fishery closure area and/or is in an area outside of the fishing footprint.
[b] It falls below the defined cut-off point of fishing effort within any one year.
[c] It has been exposed to a level of fishing effort above the defined cut-off point within any one year.
[d] Overlapping with other VMEs.
[e] Point at which trawl duration/length exceeds VME indicator patch size within the habitat. High values indicates a low sensitivity and vice versa.
[f] Proportion of discrete VME without protection.
[g] Number of cells consistently fished above the impact cut-off value over time as a proportion of the total cells impacted.
[h] A quantitative evaluation using NAFO SAI assessment approach.
[i] A qualitative category evaluated using expert judgment.

According to this evaluation, sponge grounds and gorgonian VME were considered at low overall risk of impact, meanwhile sea pen fields were considered at high overall risk.

3. Discussion

3.1. Spatial management as an approach to preventing by-catch and discards

Gear technologies (e.g. modification of fishing gear design), changes in fishing practices (e.g. depth restrictions) or switch gear types in order to avoid interactions with cold-water corals and sponges, are difficult to apply in bottom fisheries. These measures can effectively reduce by-catch of fishes and certain invertebrates (e.g. crustaceans), but they are unlikely to substantially reduce the impact on benthic communities, particularly by-catch of sessile VME indicator species with erect and fragile body forms [32]. Moreover, avoiding catches is considered preferable to attempts to minimize mortality, since discarded cold-water corals and deep-sea sponges are unlikely to reattach to the substrate [33].

Spatial management is likely to be the most effective approach for the protection of vulnerable benthic fauna from impacts of potential anthropogenic activities affecting the deep-sea ecosystems [32,34–36]. So, the most widespread management measure to address the problem is the implementation of areas closed to bottom fishing [8,37–40]. Precautionary approach is important in deep-sea conservation [36]. Spatial measures, combined with precautionary measures to freeze the footprint of bottom fishing, are effective for protecting cold-water corals and deep-sea sponge ecosystems. Area closures prevent the interactions between commercial bottom fishing gears and VME, avoiding by-catch and discards of habitat forming species. Seafloor disturbance and damage to corals and sponges are more frequent in heavily fished areas than in areas with little or no fishing [41]. Freezing of bottom fishing footprint

[38,40] prevents the expansion of fishing [1] into unfished areas that may contain cold-water corals, deep-sea sponges and other vulnerable biogenic habitats.

3.2. Marine research as a basis to underpin spatial management measures

UNGA Resolution 66/88 [6] recognized that marine research, including seabed mapping, have resulted in the identification of VMEs and in the adoption of conservation and management measures in the high seas (e.g. closed areas, according to paragraph 119b of Resolution 64/72 [5]). Additionally, in 2016 at the UNGA workshop on impacts of bottom fishing [42], special attention was drawn to the international efforts undertaken to enhance scientific knowledge on VMEs and deep-sea fisheries, through scientific research programmes.[4] In the case of the northwest Atlantic Ocean, EU groundfish surveys underpin spatial management measures to protect cold-water corals and deep-sea sponges in ABJN. Catch data from these surveys have improved our knowledge on the identification, distribution and extent of VME, as well as our understanding of the impacts of fishing. This information, in combination with (i) Canadian research vessel trawl surveys data, (ii) ecosystem data (e,g. seabed mapping, dredges, CTD and submarine images) from sources such as NEREIDA [11] and (iii) fishing footprint data from the vessel monitoring system (VMS) provided by the NAFO contracting parties, have been integrated into the NAFO management process, and have led to the proposal and implementation of conservation and management measures [8]. Thanks to the analyses of the above mentioned extensive databases, nowadays NAFO is one of the most advanced RFMO in the identification and protection of VME. Moreover, the scientific knowledge of the present distribution of VMEs represents a crucial baseline to understand how anthropogenic and natural changes are affecting these habitats, as was noted by Chimienti et *al.* [22].

There are other examples in the northern hemisphere of the use of survey trawls as VME data source, at large spatial scale. In the eastern coast of Canada, annual research vessel trawl surveys provided distribution and diversity data to underpin the Coral and Sponge Conservation Strategy [43]. Trawl data was used to delineate concentrations of sea pens, gorgonian corals and sponges applying the NAFO methodology [44] as well as to predict VMEs distributions and identify Significant Benthic Areas [45–48]. Moreover, Clarke et al. [49] indicates that the most comprehensive picture of cold-water coral and sponge presence off Alaska and the United States of America (US) west coast, comes from annual groundfish bottom trawl surveys conducted in trawlable grounds at depths from 55 to 1,280 m.

3.3. Groundfish surveys: advantages, disadvantages, ethical aspects and alternative methods

Groundfish surveys have several advantages as data sources in the NAFO Regulatory Area: (i) distribution data are collected in an annual basis, providing a valuable and systematic broad-scale monitoring of VME status [29] in trawlable grounds, and (ii) existence of long time data series, with a wide spatial and bathymetrical sampling coverage. Nevertheless, groundfish surveys have a main disadvantage: despite the occasional trawling in VME areas and the short duration of the scientific survey trawls, they can produce impacts on cold-water corals and deep-sea sponges. This poses an ethical dilemma between the need of data for the assessments and the "Precautionary Principle" [50]: groundfish surveys in ABNJ can potential harm to VMEs [51], but can significantly contribute, in the long term, to the sustainability of commercial deep-sea fisheries, thanks to the management measures based on survey data series (e.g. Total Admissible Catches of fish stocks, VME protection areas). According to the recommendations on the effectiveness of ocean observation [52], groundfish surveys provided high-quality, robust and timely data to the scientific community, society, stakeholders and policymakers, and their results are routinely integrated into the advisory processes, being essential to underpin management policies. A similar kind of tensions was identified by Crozier et al. [53] regarding ecological research. To move forward in solving this concern, there are several studies in progress focused on the effects on fish stock assessments of excluding groundfish surveys trawls from the VME closed areas, and if this exclusion compromises the quality of index data used in the assessments [54,55]. This is a key issue from the NAFO fisheries management perspective [56,57], due groundfish surveys are essential for the assessments.

In VME areas, non-invasive sampling methods (e.g. drop cameras, towed camera, remotely operated vehicles, autonomous underwater vehicles, benthic samplers, etc.) could be an alternative for monitoring of VME [58–60]. These methods are generally expensive and more appropriate at small spatial scales [29]. Particularly, visual methodologies are more accurate and efficient for studying abundance of benthic populations in small areas (e.g. seapens), but they are often not appropriate for studying their biomass and size structure [59,61]. However, NEREIDA programme made substantive progress in the use of non-invasive sampling techniques to monitor VMEs in the NAFO Regulatory Area. In this regard, several *in situ* benthic visual surveys using remotely operated vehicle (ROV) were conducted within the NAFO footprint, on board the Canadian research vessel *CCGS Hudson*, in order to provide further description of the NAFO closed areas [62,63]. This work was the basis for management decisions such as the extension of the lower bathymetric boundary of NAFO Area 5 closure up to the 2, 500 m contour [64], with the aim of protecting the entire gradient of coral and sponges identified around this area.

Chimenti et al. [59,61] suggested that trawl data is still necessary to identify areas of high concentrations of cold-water corals (e.g. sea pen fields) at large scale, but ROV images could be used afterwards to monitor these concentrations in a non invasive way, consistent with the precautionary approach. In NAFO Regulatory Area (2,707,895 km^2), as in other large fishing areas, a visual assessment with underwater visual methods (e.g. ROV) to map the entire distribution of VMEs is not feasible [65]. Additional research will be needed about the calibration and validation [61,66] of new non-invasive surveys with traditional bottom trawl surveys to enable a future combined series of data for monitoring purposes [29,63]. The work undertaken during the NEREIDA project provided good baseline data for *in situ* observations [67]. So, it will be necessary to consider plans for the deployment of non-invasive surveying methods in closed areas, including a period of comparative surveying to ensure calibration between the new and old methods [57, 61].

3.4. International collaboration for the conservation of deep-sea ecosystems

The UNGA Resolutions assigned a principal role to regulate the high seas fisheries to the RFMOs and international Agreements. Only where there are no such instruments, the flag state has the primary role of determining conservation and management measures by itself [68]. So, RFMOs are essential multilateral instruments to facilitate the implementation of VME conservation measures in the high seas, including the mitigation of cold-water coral and deep-sea sponges by-catches and discards. In the case of the high seas of the northwest Atlantic Ocean, NAFO has integrated research survey data into his "ecosystem management cycle" [20]. Based on scientific advice, NAFO has delineated and closed VME areas to bottom-contact fishing gears for conservation and management purposes [8]. Moreover, there are several successful examples about international collaboration between NAFO contracting parties to address the study and protection of VMEs within the NAFO Regulatory Area: (i) sharing and multiple use of groundfish survey data

[4] During the workshop, the EU groundfish surveys and NEREIDA programme were presented as a case study (https://www.un.org/depts/los/reference_files/Bottom_Fishing_Workshop_2016_Presentations.pdf).

[13], (ii) collection of ecosystem data through the NEREIDA programme lead by Spain with contribution from Canada, UK and Russia (https://www.nafo.int/About-us/International-Cooperation), (iii) ATLAS (www.eu-atlas.org) and SPONGES (http://www.deepseasponges.org) international research projects funded by the EU, which provided results, based on groundfish survey data, supporting the advice on VMEs [67] and contributing to implement the *Galway Statement on Atlantic Ocean Cooperation*.[5] Conversely, the non-existence of RFMOs (as in the case of the SW Atlantic high seas fishing grounds) means the absence of multilateral forums for providing and debating research data (e.g. VME data) in order to prepare advice and agree on conservation and management measures. Consequently, international policies on sustainable fisheries could be hampered by the absence of RFMOs [11].

4. Conclusions

RFMOs are essential instruments for sustainable management of high seas fisheries. In the northwest Atlantic Ocean, the integration of survey data in the NAFO management process underpins conservation and management spatial measures. Spatial management (e.g. area closures) is an effective approach for VME protection: the areas closed to bottom fishing implemented by NAFO, mitigate by-catch of VME-defining species, because they prevent the use of commercial bottom fishing gears in cold-water coral and deep-sea sponge areas. Groundfish survey data had particular relevance to delineate the boundaries of such closures, in order to reduce by-catch in the commercial bottom fisheries. EU groundfish surveys, thanks to their extensive temporal, spatial and bathymetric sampling coverage, have played an essential role in the advice on VMEs and closed areas. Nevertheless, survey trawls can produce occasional impacts on cold-water corals and deep-sea sponges. In VMEs areas, the use of alternative non-invasive sampling methods could be investigated with the aim of addressing their current limitations and developing them in the near future.

Funding

This work contributes to the European Union's Horizon 2020 research and innovation programme under grant agreement No 678760 (ATLAS). This output reflects only the author's view and the European Union cannot be held responsible for any use that may be made of the information contained therein. EU NAFO groundfish surveys has been co-funded by the European Union through the European Maritime and Fisheries Fund within the National Program of collection, management and use of data in the fisheries sector and support for scientific advice regarding the Common Fisheries Policy. The authors were supported by ATLAS (PDM, MS & AGA), NEREIDA grant agreement SI2.770786 (PDM & MS) and IEO-BIOPESLE-4 (ER).

Declaration of competing interest

None.

Acknowledgements

We are especially grateful to all the scientific staff involved in NAFO EU groundfish surveys for facilitating the data collection and to the crew of the *RV Vizconde de Eza* for assistance at sea. We want to thank also, all the people involved in the NAFO Working Group on Ecosystem Science and Assessment (WGESA) - formerly named Working Group on Ecosystem Approach to Fisheries Management (WGEAFM) - for their contributions and discussions on VMEs issues. Finally, we would also like to thank the three anonymous reviewers for their valuable feedback and suggestions to improve the manuscript.

[5] In 2013, the EU, the US and Canada signed the *Galway Statement on Atlantic Ocean Cooperation*, which aims to join forces on the Atlantic Ocean research, in order to better understand this Ocean and promote the sustainable management of its resources.

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Glossary

ABNJ: Areas beyond national jurisdictions
ATLAS: A Trans-Atlantic assessment and deep-water ecosystem-based spatial management plan for Europe (international research project founded by the European research programme Horizon 2020)
BIOPESLE-4: Biology of exploited species in long distance fisheries (Spanish research project)
CEM: Conservation and Enforcement Measures
CTD: Conductivity, temperature and depth sensor
ECOVUL/ARPA: Study of vulnerable ecosystems and their relationships with fishing gears (Spanish research project)
EU: European Union
FAO: United Nations Food and Agriculture Organization
GIS: Geographic Information System
IEO: Spanish Institute of Oceanography
NAFO: Northwest Atlantic Fisheries Organization
NEREIDA: NAFO potential vulnerable marine ecosystems impacts of deep-sea fisheries (international research project, lead by Spain)
RFMO: Regional Fisheries Management Organization
SAI: Significant Adverse Impact
SPONGES: Deep-sea Sponge Grounds Ecosystems of the North Atlantic, an integrated approach towards their preservation and sustainable exploitation (international research project founded by the European research programme Horizon 2020)
UNGA: United Nations General Assembly
US: The United States of America
USC: University of Santiago de Compostela. Galicia. Spain
VME: Vulnerable Marine Ecosystem
VMS: Vessel Monitoring System
WGEAFM: Working Group on Ecosystem Approach to Fisheries Management
WGESA: Working Group on Ecosystem Science and Assessment